The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents

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Abstract—We have collected and self-consistently analyzed data for per-capita consumption of artificial light, per-capita gross domestic product, and ownership cost of light. The data span a wide range (three centuries, six continents, five lighting technologies, and five orders of magnitude), and are consistent with a linear variation of per-capita consumption of light with the ratio between per-capita gross domestic product and ownership cost of light. No empirical evidence is found for a saturation in per-capita consumption of light, even in contemporary developed nations. Finally, we extrapolate to the world in 2005, and find that 0.72 percent ($437B/year) of world gross domestic product and 6.5 percent (29.5 Quads/year) of world primary energy was used to produce 130 Plmh/year of artificial light.

Keywords—Solid-state lighting, Rebound effect, Energy efficiency, Price elasticity, Income elasticity, Global lighting demand.

1 INTRODUCTION

Artificial light has long been a significant factor contributing to the quality and productivity of human life. It expands the productive day into the nonsunlit hours of the evening and night, and during the day it expands productive spaces into the nonsunlit areas of enclosed dwellings, offices and buildings (Bowers 1998; Boyce 2003; Schivelbusch 1988).

Because we value artificial light so highly, we consume huge amounts of energy to produce it. As estimated later in this paper, the production of artificial light consumed roughly 6.5 percent of total global primary energy in 2005. This percentage is large and, coupled with increasing concern over energy consumption, has inspired a number of projections of light and associated-energy

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consumption into the future (Kendall and Scholand 2001; Navigant 2006; Tsao 2002). Such projections are of special interest at this point in history when lighting technologies are evolving rapidly. Filament-based incandescent technology is giving way to gas-plasma-based fluorescent and high-intensity-discharge (HID) technology; and over the coming 5–10 years both may give way to solid-state-lighting (SSL) technology (Krames and others 2007; Schubert, Kim, Luo, and Xi 2006; Shur and Zukauskas 2005; Tsao 2004).

Projections of the consumption of light and associated power are difficult, however, because there is no consensus regarding the factors that underlie the demand for light. Hence, relatively arbitrary assumptions must be made, the most common of which is that demand for light is independent of the efficiency (and hence cost) with which it is produced and delivered. If true, then technology evolution leading to efficiency improvement would not lead to an increase in light consumption, but rather to a decrease in energy consumption. If not true, however, there might instead be an increase in light consumption, a type of "rebound" effect (Brookes 1990; Khazzoom 1980) that would lessen the decrease in energy consumption.

Indeed, the possibility of rebound effects is of intense current interest (UKERC 2007) not just for lighting, but for all energy services (for example, transport of people and goods, heating and cooling of spaces, and process machinery and appliances). These services are the dominant consumers of energy in our modern economy, and whether (and by how much) improvements in their energy efficiencies increase or decrease energy consumption has important ramifications on public policies aimed at reducing energy consumption and risk of human-induced climate change.

Because of the importance of possible rebound effects, much work has been expended trying to understand and quantify them, both theoretically (Saunders 1992) and empirically (Greening, Greene, and Difiglio 2000). For any particular energy service, however, its magnitude has been difficult to quantify, especially over longer time periods for which its magnitude can be anticipated to be largest. Nearly all empirical studies of which we are aware focus on relatively short (months to years) time periods during which societal-use paradigms for an energy service are relatively static. It is only over longer (decades to centuries) time periods that radically new societal-use paradigms may be expected to emerge, with associated radical changes in consumption of that service (Rosenberg 1982). It is in fact these radically new societal-use paradigms that were envisaged in the first formulation of the rebound effect (Alcott 2005; Jevons 1906).

Recently, a number of careful estimates have been made of the consumption of light in various nations over diverse geographic, economic and temporal circumstances. In this work, we have built on these estimates – filling in gaps in the datasets, estimating demand factors auxiliary to the datasets, and self-consistently integrating the datasets – to create a quantitative picture of the consumption of light. These estimates span a wide enough (over five orders of magnitude) dynamic range to enable accurate correlations between the consumption of light and its underlying demand factors. They also span a long enough (decades to centuries) time period to enable quantitative conclusions to be drawn about the rebound effect in this important energy service over historically significant time scales.

Indeed, lighting appears to be uniquely well suited among the various energy services for such a quantitative study. Its output (light), is more easily defined and estimated than the outputs (for example, weight times distance traveled, or change in temperature times volume or heat capacity of space) of other energy services. Though it has had a long history of technology innovation, each major lighting technology has had a reasonably well-defined historical period of maturity or dominance, without the accounting difficulties associated with a massive proliferation of subtechnology variants, each with a different energy efficiency, market penetration and cost structure.

The remainder of this paper is organized as follows. In Section 2, we discuss how the estimates, taken from a number of sources, were self-consistently analyzed and interpreted. In Section 3, we discuss the primary empirical trend: that consumption of light varies linearly with the ratio between gross domestic product and cost of light. In Section 4, we extrapolate and aggregate these trends to estimate world consumption of light and associated energy.

2 DATA, ESTIMATES, AND ASSUMPTIONS

In this Section, we discuss estimates of the consumption of light, along with how we have built on these estimates – filling in gaps in the datasets, estimating demand factors auxiliary to the datasets, and self-consistently integrating across the datasets – to create a quantitative picture of the consumption of light and associated power. We organize our discussion according to the quantity being estimated: consumption of light, luminous efficacy, costs of energy and light, consumption of associated energy, and finally gross domestic product and population. Before we begin, though, we make a few comments regarding scope, nomenclature and units.

Monetary units. For the most part (particularly in Table 1, which summarizes the main results of this paper), monetary units are year 2005 US$, using exchange rate conversions across nations from the XE Interactive Currency Table (XE) and deflation conversions across years from Measuring Worth (MW).

Light and associated energy units. We choose as our units for light and associated energy: petalumen-hours (Plmh) and petawatt-hours (PWh). These units are large, but appropriate for nation-scale quantitites. As the usual unit for time scale of consumption is the year, we then choose as our units for the consumption of light and associated energy: petalumen-hours per year (Plmh/year), denoted by the symbol Φ, and petawatt-hours per year (PWh/year), denoted by the symbol $\dot{E}_\Phi$. We will often refer to these quantities as consumption of light and energy, though precisely speaking they are consumption of light and *power.* Also, we choose as our unit of population billions of persons (Gper), so that our units for per capita rates of consumption of light and associated energy become: megalumen-hours per person-year (Mlmh/(per-yr)), denoted by the symbol φ, and megawatt-hours per person-year (MWh/(per-yr)), denoted by the symbol $\dot{e}_\Phi$. Analogously, we denote gross domestic product *GDP*, with units of billions of dollars per year G$/year, and we denote per capita gross domestic product *gdp*, with units of dollars per person-year ($/(per-yr)).

Illumination vs. signaling. Our focus throughout is on consumption of light in those applications in which light is used to illuminate (and hence is viewed indirectly, after it scatters from an object or scene) rather than those in which light is used to signal or display information (and hence is viewed directly). We note here that the energy economics of these two broad classes of applications for light are quite different. For illumination, the cost of light is mostly the cost

Nation or Nations	Year	Predominant Energy Source or Lighting Technology	per capita Consumption of Light (φ)				per capita Consumption of Associated Energy ($\dot{e}_{\varphi}$)				Luminous Efficacy (η_{φ})				Cost of Energy (*CoE*)				Cost of Light (*CoL*)				Population, *GDP*, *gdp*			Predicted Consumption of Light and Associated Energy			
			Vehicle	Grid Electricity	Fuel-Based	All	Vehicle	Grid Electricity	Fuel-Based	All	Vehicle	Grid Electricity	Fuel-Based	φ-Weighted Inverse Average	Vehicle	Grid Electricity	Fuel-Based	All	Vehicle	Grid Electricity	Fuel-Based	All	Population (*N*)	Gross Domestic Product (*GDP*)	per capita gross domestic product (*gdp*)	per capita Consumption of Light $\beta \cdot gdp/CoL$	per capita Consumption of Energy $\beta \cdot gdp/[(1+\kappa_{\varphi}) \cdot CoE]$	Consumption of Light $\beta \cdot GDP/CoL$	Consumption of Energy $\beta \cdot GDP/[(1+\kappa_{\varphi}) \cdot CoE]$
			Mlmh/(per-yr)				MW$_e$h/(per-yr)				lm/W$_e$				\$/MW$_e$h				\$/Mlmh				Gper	G\$/yr	\$/per-yr	Mlmh/per-yr	MW$_e$h/per-yr	Plmh/yr	PW$_e$h/yr
UK	1700	Can			0.00058	0.00058			0.0068	0.0068			0.085	0.085			2,188	2,188			29,253	29,253.1	0.0086	16	1,863	0.00046	0.0046	0.0000039	0.000039
UK	1750	Can			0.00060	0.00060			0.0065	0.0065			0.092	0.092			2,360	2,360			29,386	29,385.8	0.0125	27	2,120	0.00052	0.0048	0.0000064	0.000060
UK	1800	Can+Oil			0.00274	0.00274			0.0247	0.0247			0.111	0.111			1,439	1,439			14,846	14,846.5	0.0183	44	2,414	0.00116	0.0090	0.0000212	0.000164
UK	1850	Gas+Can			0.01288	0.01288			0.0271	0.0271			0.475	0.475			576	576			1,386	1,385.7	0.0272	94	3,472	0.01792	0.0323	0.0004865	0.000878
UK	1900	Gas+Ker			0.26728	0.26728			0.3519	0.3519			0.759	0.759			345	345			520	519.6	0.0412	275	6,693	0.09212	0.1038	0.0037864	0.004272
UK	1950	Inc		5.0		4.98733		0.43		0.4299		12		11.600		182		182		20.9		20.9	0.0501	518	10,340	3.53664	0.3045	0.1770546	0.015263
UK	2000	Inc+Flu+HID	0.32	46.1		46.40813	0.0146	0.85		0.8681	22	54		53.462	748	73		84	45	1.8		2.1	0.0595	1,788	30,037	102.38166	1.9126	6.0862195	0.113843
US	2001	Inc+Flu+HID	1.22	134.9		136.10575	0.0552	2.68		2.7392	22	50		49.688	278	72		76	17	1.9		2.0	0.2850	12,039	42,237	147.49985	2.9647	41.9872430	0.845015
China	2006	Inc+Flu+HID	0.13	16.2		16.38264	0.0074	0.28		0.2876	18	58		56.964	441	79		88	33	1.8		2.1	1.3108	11,842	9,034	31.33592	0.5494	41.0233608	0.720163
FSU	2000	Inc+Flu+HID	0.18	38.5		38.70621	0.0103	0.90		0.9061	18	43		42.717	235	49		51	17	1.5		1.6	0.2891	1,918	6,636	29.83051	0.6974	8.6133565	0.201640
OECD Eur	2005	Inc+Flu+HID	0.24	45.7		45.92144	0.0109	0.85		0.8569	22	54		53.591	944	138		149	57	3.4		3.7	0.4859	13,800	28,404	54.89360	1.0230	26.6360540	0.497023
JP+KR	2005	Inc+Flu+HID	0.31	71.6		71.93434	0.0141	1.10		1.1160	22	65		64.457	799	142		150	48	2.9		3.1	0.1761	5,452	30,967	71.22009	1.1035	12.5228322	0.194283
China	2005	Inc+Flu+HID	0.14	13.2		13.36237	0.0080	0.23		0.2359	18	58		56.644	374	78		88	28	1.8		2.1	1.3032	10,717	8,224	28.39031	0.5006	36.9504567	0.652329
AU+NZ	2005	Inc+Flu+HID	0.49	63.0		63.45005	0.0222	1.28		1.3071	22	49		48.541	568	98		106	34	2.7		2.9	0.0241	836	34,671	84.86073	1.7460	2.0447243	0.042123
Wrld Grid	2005	Inc+Flu+HID	0.18	32.7		32.87727	0.0082	0.65		0.6584	22	50		49.933	600	110		116	36	2.9		3.1	4.0767	54,821	13,447	31.04136	0.6209	126.3851468	2.531114
China	1993	Inc	0.13	2.6		2.70515	0.0074	0.10		0.1108	18	25		24.415	168	104		109	12	5.6		5.9	1.1784	4,059	3,445	4.15132	0.1698	4.8858277	0.200116
Wrld Non-Grid	1999	Ker			0.04275	0.04275			0.1228	0.1228			0.348	0.348			183	183			600	600.2	2.0000	4,404	2,202	0.02624	0.0646	0.0524084	0.129221
Wrld	2005	Ker+Inc+Flu +HID												47.527				119				3.3	6.4234	60,670	9,445	20.19001	0.4243	129.5222906	2.725241

TABLE 1

Per-capita consumption of light (φ) and associated energy ($\dot{e}_{\varphi}$), luminous efficacies (η_{φ}), costs of energy (*CoE*) and light (*CoL*), population (*N*), gross domestic product (*GDP*) and per capita gross domestic product (*gdp*), for the five datasets (in brown, blue, pink, grey and green) discussed in Section 2. Estimates are also given for aggregate luminous efficacy and costs of light and associated energy for the World 2005. Monetary units are all year 2005 US\$. The various nation abbreviations are: UK = United Kingdom; FSU = Former Soviet Union; OECD Eur = Organization for Economic Cooperation and Development Europe = Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, UK, Ireland, Greece, Portugal, Spain, Hungary, Poland, Czech Republic, Slovak Republic, Turkey, Iceland, Luxembourg; JP+KR= Japan + South Korea; AU+NZ = Australia + New Zealand; Wrld = World. The various lighting technology abbreviations are: Can = candle; Oil = oil; Gas = gas; Ker = kerosene; Inc = incandescence; Flu = fluorescence; HID = high-intensity discharge. The various energy-source sectors are vehicle, grid electricity and fuel-based. As discussed in the introduction to Section 2, in order to more easily compare and aggregate the various energy-source sectors, we use for the energy consumption units of the vehicle and fuel-based energy-source sectors Watts (W$_e$) of electrical power that would have been available had the Watts (W$_c$) of primary chemical power been converted and transported to point of use. The conversion factors used were σ_{veh} = 0.15 W$_e$/W$_c$ and σ_{grid} = 0.316 W$_e$/W$_c$, respectively. Note that cost of light (\$/Mlmh), which is proportional to the ratio between cost of energy (\$/MW$_e$h) and luminous efficacy (lm/W$_e$), is independent of energy consumption unit.

of the energy that is converted into light;[1] while for signaling or information display, the cost of light is mostly the cost of the capital equipment used to convert energy into light.[2] Hence, by including illumination but not signaling or information display, we are focusing on those applications for light which are most energy-intensive.

Vehicle, grid-electricity and fuel-based energy-source sectors. Within the broad class of illumination applications, our intent is to be comprehensive, and hence to include consumption of light produced from all types of energy sources: from electricity in those populations with access to the electrical grid, from chemical fuel in those populations without access to grid electricity, and from electricity produced *in situ* from chemical fuel in vehicles. We think of these as defining three energy-source sectors and, for simplicity, refer to them as the grid-electricity, fuel-based, and vehicle energy-source sectors. We note that, even in modern times, the fuel-based sector is not insubstantial. It has been estimated that, as recently as 1999, 2 billion persons did not have access to grid electricity and were largely dependent on kerosene lamps for their lighting (Mills 2005).

Electricity vs. chemical fuels. We keep track of the different “natural” units of energy associated with these different energy-source sectors by using subscripts (“e” for electricity and “c” for chemical), then convert between units by assuming efficiencies for the conversion of chemical fuel to electricity followed by transport of the electricity to point-of-use. For grid electricity, we use an efficiency of σ_{grid}=0.316 W_e/W_c (DOE, 2007). For vehicle electricity, we use an efficiency of σ_{veh}=0.15 W_e/W_c, which is basically the product of engine (assuming a mix of gas and diesel) and alternator efficiencies (Navigant 2003). Thus, luminous efficacies (denoted by the symbol η_φ) in units of lm/W_c are equivalent to those in units of lm/W_e multiplied by one of these efficiency factors: the luminous efficacy of an incandescent lamp powered by grid electricity could either be written as 14 lm/W_e or 4.4 lm/W_c, depending on whether one chooses units of wall-plug grid electricity or units of the primary chemical energy used to produce that wall-plug electricity. Similarly, per capita consumption of energy in units of MW_ch/(per-yr) is equivalent to that in units of MW_eh/(per-yr) divided by one of these efficiency factors; and costs of energy (*CoE*) in units of \$/MW_ch are equivalent to those in units of \$/MW_eh multiplied by one of these efficiency factors.

Comparing and aggregating across energy-source sectors. Of primary interest in this paper are the consumption and cost of light, neither of which depend on the choice of energy units (W_e or W_c) just discussed. However, because important intermediate quantities such as consumption of energy, luminous efficacy and cost of energy *do* depend on the choice of energy units, and because we wish to compare and aggregate these intermediate quantities (see Table 1), we must choose a common energy unit. One possible choice is W_c, since chemical fuel is the starting point of the vast majority of energy for lighting, past and present.

[1] A typical 30W compact fluorescent light bulb (equivalent to a 100–150W incandescent light bulb) had, in early 2008, a retail capital cost of about $3, but, powered by electricity at $0.08/kWh, will use about $19 worth of electricity over a typical 8,000-hour operating life (*http://www.bulbs.com/eSpec.aspx?ID=13178&Ref=Compact+Fluorescent+Screw-in&RefId=20&Ref2=Light+Bulbs*).

[2] A typical 48W 22” liquid-crystal display television had, in early 2008, a retail capital cost of about $400, but, powered by electricity at $0.08/kWh, will only use about $200 worth of electricity if used over its product life of 50,000 hours (6 hours per day for 23 years), less if used for less than its product life, as is typical for advanced consumer electronics (*http://www.viewsonic.com/products/lcdtv/NX2232w/*).

However, that choice is unnatural and confusing for quantities such as the luminous efficacy of today's grid-electricity-powered lamps (for example, the 4.4 lm/W_c calculated above for an incandescent lamp). Therefore, we choose instead W_e, which makes natural and intuitive those quantities associated with the (currently much larger) grid-electricity energy-source sector, though making somewhat unnatural and nonintuitive those associated with the (currently much smaller) vehicle and fuel-based energy-source sectors.

Time-series vs. cross-sectional data. As discussed in the Introduction, we are purposefully interested in changes in consumption of light over the longer (decades to centuries) time periods required for radically new societal-use paradigms to emerge. Over such long time periods, we assume light consumption to have reached a near-steady-state response to these new societal-use paradigms, so that we can combine and treat on the same footing historical time-series (in one country over time) data with contemporary cross-sectional (across many countries at the same time) data. The degree to which steady-state has been achieved may vary from time period to time period and from country to country, however, and is a potential source of error in our analysis.[3]

2.1 CONSUMPTION OF LIGHT

The starting point for our estimates of the consumption of light is the five datasets summarized in Table 1. The first dataset (in brown) we refer to as the "Fouquet-Pearson" dataset: it represents estimates from the monumental work by Fouquet and Pearson on consumption of light in the United Kingdom over a 300-year time span (Fouquet and Pearson 2006). The second dataset (in gray) we refer to as the "IEA" dataset: it represents estimates from the recent comprehensive study by the International Energy Agency on consumption of light in various nations or groups of nations for which grid electricity is available, mostly in the year 2005 (IEA 2006). The third dataset (in blue) we refer to as the "Navigant" dataset: it represents an estimate from the extremely thorough bottoms-up survey by Navigant of consumption of light in the United States in 2001 (Navigant 2002). The fourth dataset (in green) we refer to as the "Mills" dataset: it represents estimates by Mills and co-workers of the consumption of light in China in 1993 (Min, Mills, and Zhang 1997) and in populations in 1999 for which grid electricity was not available (Mills 2005). The fifth dataset (in red) we refer to as the "Li" dataset: it represents an estimate of consumption of light in China in 2006 (Li 2007a).

Of the estimates in these datasets, we consider those of contemporary consumption of light to be much more accurate than those for historical consumption of light. Despite the care with which the historical estimates were made, such estimates are fraught with difficulties, not the least of which are assumptions on the mix of lighting technologies used during periods when the efficiencies (or luminous efficacies) of these technologies were evolving rapidly. And, of the estimates of contemporary consumption of light, we consider that of the United States in 2001 to be the most accurate, and those for China in 1993 and 2006 to be the least accurate.

[3] For example, the lower-than-expected consumption of light for the data points associated with China (1993, 2005, 2006) seen in Figure 3 may be due to a lag time associated with consumption of light keeping pace with the extremely rapid rate at which *gdp* has grown in that nation.

All five of the datasets provide estimates of consumption of light for two of the energy-source sectors (grid electricity and fuel-based). Although it is a small (of order 1 percent) contribution, for completeness we have added to the contemporary (post 1950) data estimates of consumption of light for the third energy-source sector (vehicles). To do this, in anticipation of the result for all energy-source sectors discussed in Section 3, we assume that per-capita consumption of light associated with vehicles is simply proportional to the ratio of the *gdp* (\$/(per-yr)) of a nation (or group of nations) to the cost of light (*CoL*, in \$/Mlmh) in that nation (or group of nations):

$$\varphi_{veh} = \beta_{veh} \cdot \frac{gdp}{CoL_{veh}}\,. \tag{1}$$

For the proportionality constant we use β_{veh}=0.000485, deduced from Navigant's study of consumption of light in vehicles (autos, buses and trucks) in the United States in 2002 (Navigant 2003), where we have summed over only those lamps (high- and low-beam headlamps, parking lamps, license plate lamps and fog lamps) used for illumination (rather than signaling) purposes. For *gdp* we use the estimates discussed in Subsection 2.6. For cost of light we use the expression discussed in Subsection 2.4, but particularized for vehicles: $CoL_{veh} \approx (1+\kappa_\varphi)\cdot CoE_{veh}/\eta_{\varphi,veh}$.

Finally, for each nation or group of nations, we sum the estimates of consumption of light from the three energy-source sectors to get an aggregate consumption of light across those sectors.

2.2 LUMINOUS EFFICACY

Luminous efficacy represents the efficiency with which energy is used to produce visible light. As has been discussed recently, there is a limiting luminous efficacy for the production of high quality white light which renders well the colors of typical environments. For a correlated color temperature (CCT) of 3,800K and a color rendering index (CRI) of 85 (market-weighted averages for the U.S. in 2001), this is roughly 400 lm/W_e (Tsao and others 2009). In practice, the luminous efficacies of various lighting technologies are far less than this limiting value, and have evolved throughout history. Indeed, as discussed first by Nordhaus (Nordhaus 1997), they have evolved spectacularly – a key insight in the development of "hedonic" indices based on the price of consumed services or features rather than of the inputs to those services or features.[4]

For all of the datasets, luminous efficacies were estimated directly, based on an understanding of the lighting technologies in use in a particular nation or groups of nations, and at a particular point in time. Then, because of the relationship between luminous efficacy (η_φ, in lm/W), per-capita consumption of light (φ, in Mlmh/(per-yr)) and associated energy ($\dot{e}_\Phi$, in MWh/(per-yr)),

$$\frac{\varphi}{\eta_\varphi} = \dot{e}_\varphi, \tag{2}$$

one of the other quantities could be estimated and the third inferred. For example, in the Fouquet-Pearson dataset consumption of energy and luminous efficacy were estimated and consumption of light was inferred. Or, for example,

[4] See, e.g., U.S. Department of Labor discussions of hedonic adjustments to the U.S. consumer price index (*http://www.bls.gov/cpi/home.htm*).

in the Navigant dataset consumption of light and luminous efficacy were estimated and consumption of energy was inferred.

For the most part, we have used "as is" the estimates of luminous efficacy in the original datasets. The only exception was in the Fouquet and Pearson dataset, for which luminous efficacies were based on an evolved weighting of the proportions of old and new lighting technologies, with the underlying luminous efficacies of the various technologies based on estimates from Nordhaus' classic study (Nordhaus 1997). In this dataset, the luminous efficacy for 2000 appeared to be biased towards incandescent technology rather than reflecting a more accurate modern mix of incandescent, fluorescent and high-intensity discharge (HID) technology. Hence, instead of Fouquet and Pearson's estimate of 25 lm/W_e (based on Nordhaus' original estimate), we substituted the 2005 OECD Europe aggregate average of 54 lm/W_e from the IEA dataset.

Note that luminous efficacy relies on an assumption regarding the source of energy that is used to produce light, and these in turn differ according to the energy-source sectors (vehicle, grid electricity, and fuel-based) discussed in the introduction to Section 2. To compare across these sectors, and because electricity is now and likely in the future the dominant source of energy for lighting, we list in Table 1 luminous efficacies in units of lm/W_e, calculated as if electricity were the initial energy source.

For the grid electricity and vehicle energy-source sectors, the most common units for luminous efficacy are lm/W_e, calculated as if electricity were the initial energy source, and so these are listed "as is" in Table 1. Note that for the vehicle sector the range of luminous efficacies is not very great, varying from the $\eta_{\varphi,veh}$=18 lm/W_e typical of tungsten incandescent bulbs to the $\eta_{\varphi,veh}$=24 lm/W_e of tungsten-halogen incandescent bulbs (Denton 2004, p. 292). In newer vehicles, the latter is more common, and so we have assumed luminous efficacies for the various nations and groups of nations closer to the latter for recent years in more developed nations, and closer to the former for less recent years in less developed nations.

For the fuel-based energy-source sector, the starting point is the luminous efficacy in units of lm/W_c calculated as if chemical fuel were the initial energy source. Then, we divide by the σ_{grid}=0.316 W_e/W_c efficiency of conversion-and-transport-to-point-of-use factor to get the effective luminous efficacy in units of lm/W_e as if grid electricity were the initial energy source.

Finally, given the luminous efficacies and per-capita consumptions of light of the various sectors for a particular nation or group of nations, an aggregate luminous efficacy for all the sectors combined is calculated by averaging the inverse luminous efficacies of each sector weighted by the fraction of light consumed per capita by that sector,

$$\frac{\varphi}{\eta_\varphi} = \frac{\varphi_{grid}}{\eta_{\varphi,grid}} + \frac{\varphi_{fuel}}{\eta_{\varphi,fuel}} + \frac{\varphi_{veh}}{\eta_{\varphi,veh}}, \tag{3}$$

where $\varphi=\varphi_{grid} + \varphi_{fuel} + \varphi_{veh}$ is the per-capita consumption of light for all three sectors. This weighting allows Equation (2) to be valid for each sector individually as well as for the sum over all sectors.

2.3 COST OF ENERGY

By cost of energy (*CoE*), we mean the point-of-use cost to the consumer who is converting the energy into light. Just as for luminous efficacy, however, the initial energy source is important to keep in mind. And, just as for luminous efficacy, to compare across these sectors, and because electricity is now and likely in the future the dominant source of energy for lighting, we list in Table 1 cost of energy in units of $/MW$_e$h calculated as if electricity were the initial energy source.

For the Fouquet and Pearson historical UK dataset, we used their estimates of the cost of energy "as is," but assumed that for 1900 and earlier the dominant energy source was chemical fuel, while for 1950 and later it was grid electricity. For the IEA and Navigant datasets (except for China), we used international residential and industrial electricity prices compiled (EIA 2007b) by the U.S. Energy Information Administration.[5] For China, estimates were spliced together from a number of sources (Li 2007b).

For the Mills nongrid world, we used his estimate[6] of $0.5/liter for kerosene (in year 1999 US$), divided by the energy content of kerosene (36.5 MJ/liter), then multiplied by 60·60 s/h (number of seconds in an hour) and a year 1999 to year 2005 exchange rate conversion, to derive a *CoE* of 58 $/MW$_c$h. Then, we divide by the σ_{grid}=0.316 W_e/W_c efficiency-of-conversion-and-transport-to-point-of-use factor to get an effective *CoE* of 183 $/MW$_e$h as if grid electricity were the initial energy source.

For the vehicle sector, we use international gasoline costs per unit volume ($/gallon) taken from a compilation by the German Federal Ministry for Economic Cooperation and Development (GTZ, 2007), divided by the σ_{veh}=0.15 W_e/W_c efficiency factor, then divided by the energy content of gasoline (38.3 kW$_c$h/gallon), to get the cost of energy in $/MW$_e$h as if electricity were the initial energy source.

In all cases, for groups of nations, we used *GDP*-weighted averages.

2.4 COST OF LIGHT

By cost of light (*CoL*, in units of $/Mlmh), we mean the ownership cost of light, which includes (Azevedo, Morgan, and Morgan 2009; Dowling 2003; Rea 2000): the cost of the energy that is converted into light, the purchase and maintenance cost of the lamp (or bulb) that converts the energy into light, and the purchase cost of the luminaire and lighting system that directs and controls the light. The first cost is an operating cost, the second and third costs are capital costs.

The operating cost is the dominant of these, and is just the cost of energy divided by luminous efficacy, CoE/η_φ, with luminous efficacy and cost of energy as discussed in Subsections 2.2 and 2.3.

The purchase and maintenance cost of the lamp is smaller, and can be thought of as a fraction of the operating cost. For modern incandescent, fluorescent and high-intensity-discharge (HID) lamps, the fraction is approximately 1/6 (Navigant 2002). For the replaceable parts of modern kerosene lamps (the wick and mantle) such as those used for fuel-based lighting, the fraction has

[5] Since the cost and use of energy for lighting varies across the residential, commercial and industrial sectors, the aggregate cost of energy for lighting across these sectors can be written as: $CoE = (CoE_{Res}\cdot\dot{E}_{Res}+CoE_{Com}\cdot\dot{E}_{Com}+CoE_{Ind}\cdot\dot{E}_{Ind})/\dot{E}$, where $\dot{E} = \dot{E}_{Res}+\dot{E}_{Com}+\dot{E}_{Ind}$ is the total energy consumed for lighting. In the U.S., the cost of energy in the form of electricity for the commercial sector is, very roughly (EIA, 2007a), $CoE_{Com} \approx (2/3)\cdot CoE_{Res}+(1/3)\cdot CoE_{Ind}$, and the fractions of energy for lighting consumed by the various sectors are roughly (Navigant 2002) $\dot{E}_{Res}/\dot{E} \approx 4/9$, $\dot{E}_{Com}/\dot{E} \approx 3/9$ and $\dot{E}_{Ind}/\dot{E} \approx 2/9$. Hence, we can deduce, after some algebra, that $CoE \approx (2/3)\cdot CoE_{Res}+(1/3)\cdot CoE_{Ind}$. Though this formula is strictly valid only for the U.S., we use it, in the absence of similarly detailed inventories, for all other nations (except China) as well.

[6] Note that this cost for kerosene is an estimate averaged over many different countries and continents, and could be the source of some error.

been estimated to be very similar, approximately 1/7 (Mills 2005). For solid-state lighting (widely considered the next generation of lighting technology), the fraction estimated from industry targets (EERE, 2009) for high-color-rendering white light in the years 2012–2015 is also similar, in the range 1/5 to 1/12. We have not attempted to estimate whether these fractions also hold for past generations of more primitive lighting technologies. However, even in primitive lighting technologies, fuels appear to dominate the container for the fuels (for example, firewood in a hearth), and it is not unreasonable to assume (as did Nordhaus (Nordhaus 1997) and Fouquet and Pearson (Fouquet and Pearson 2006) in their classic historical studies of the economics of lighting) that the fractions are similarly small.

The purchase cost of the luminaire and lighting system is more difficult to estimate. It has been characterized, however, as being of the same order of magnitude as the purchase cost of the lamp (IEA 2006), and this characterization is consistent with the similarity in the projected world market of ~$94B for luminaires in 2010 (GIA, 2008) and ~$75B and in the estimated world market for lamps in 2007 (Kanellos 2008). In the absence of accurate historical and contemporary data across nations, we assume here that these costs are a similarly small fraction, 1/6 to 1/7, of the operating cost. This is an assumption, however, that would benefit from more detailed examination.

Taken together, we write the cost of light as:

$$CoL = \frac{CoE}{\eta_\varphi} \cdot (1 + \kappa_\varphi), \tag{4}$$

where $\kappa_\varphi = 1/3$ is the ratio of the capital to operating costs of light.[7] The operating fraction of the cost of light is then $1/(1+\kappa_\varphi) \sim 3/4$ and the capital fraction of the cost of light is $\kappa_\varphi/(1+\kappa_\varphi) \sim 1/4$.

To see the variation in cost of light over the various datasets, and how that variation is determined by variations in luminous efficacy and cost of energy, Fig. 1 shows a scatterplot of the datasets on an η_φ vs. *CoE* plot. The dashed diagonal lines are contours of constant CoL calculated according to Equation (4).

One sees that the cost of light varies across the datasets by ~4.3 orders of magnitude. The greater part of that variation is due to a ~2.8 order-of-magnitude variation in luminous efficacy; the lesser part is due to a ~1.5 order-of-magnitude variation in cost of energy. Note that in general the more recent data points have higher luminous efficacies and lower costs of energy. The glaring exception is the WRLD-NONGRID 1999 data point, which represents the world population in 1999 without access to grid electricity. Because of this population's reliance on relatively primitive kerosene lamp technology, its luminous efficacy is comparable to, though its cost of energy is somewhat lower than, that of the United Kingdom in the 1850's. Also note that even among the most contemporary (2000–2005) data points, there is a surprisingly large variation in cost of energy, with the FSU 2000 data point at the low end, and

[7] From the discussion above, this estimate for κ_φ is clearly more accurate for current, and less accurate for historical, lighting technologies. However, it represents a small (order of magnitude 0.5 ~ log(3)) correction to *CoL* when compared to the (order of magnitude 4.3) variation in *CoL* itself for the range of lighting technologies discussed in this paper. Indeed, we include κ_φ as a correction factor here not because it alters in any way the linearity of the relationship discussed in Section 3 between φ and *gdp*/*CoL*, but because it enables a more accurate estimate for β, the proportionality constant for that relationship.

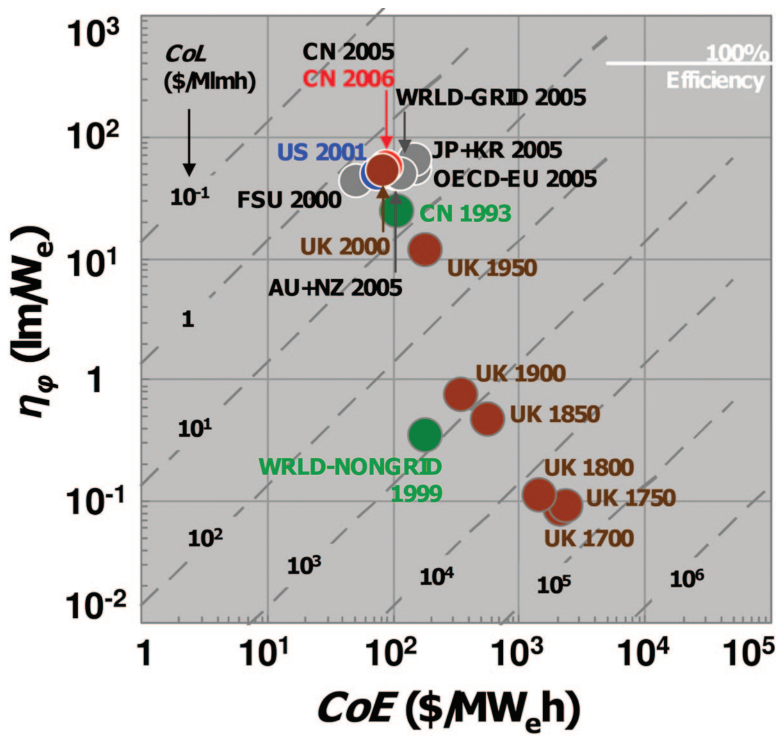


Fig. 1. Scatterplot of the luminous efficacies (η_φ) and costs of energy (*CoE*) associated with the five datasets discussed in Section 2. Country abbreviations are given in the caption to Table 1. The dashed diagonal lines are contours of constant cost of light. The horizontal white line at the upper right indicates the 400 lm/W luminous efficacy associated with 100 percent efficient conversion of energy into white light with correlated color temperature (CCT) 3,800K and CRI 85 (Tsao, Coltrin, Crawford, and Simmons, 2009).

JP+KR 2005 at the high end. There is much less variation, however, in their luminous efficacies.

2.5 CONSUMPTION OF ASSOCIATED ENERGY

By consumption of energy associated with the consumption of light we should in principle include two contributions: consumption of energy associated with the operating cost of light, and consumption of energy "embodied" in the capital cost of light.

The first contribution can be written by analogy to Equation (2): $\dot{e}_{\Phi,op}=\varphi/\eta_\varphi$. The second contribution can be written as: $\dot{e}_{\Phi,cap}=(\varphi\cdot\kappa_\varphi\cdot CoE/\eta_\varphi)/\eta_\mu$, where $\varphi\cdot\kappa_\varphi\cdot CoE/\eta_\varphi$ is the cost of the capital equipment used to produce, direct and control light (the capital cost-of-light part of Equation (4) multiplied by φ), and $1/\eta_\mu$ is the energy intensity for manufacturing that capital equipment. The ratio between the two contributions is $\dot{e}_\Phi\varphi,_{cap}/\dot{e}_{\Phi,op}=\kappa_\varphi\cdot CoE/\eta_\mu$, and contains three terms.

The first two terms we can estimate easily. The capital equipment fraction of the cost of light we estimated in Subsection 2.4 to be $\kappa_\varphi \sim 1/3$. The cost of electricity in the U.S. in 1994, per unit of chemical fuel source energy, has been estimated to be *CoE* ~ 28 $/MW$_c$h (IEA 2006).

The third term, the energy intensity for manufacturing the capital equipment for lighting, is more difficult to estimate but can be reasonably bounded. An upper bound would be that associated with the most energy intensive manufactured product group, which in the U.S. in 1994 was stone, clay and glass products, with $1/\eta_\mu \sim 15.09$ kBtu/$ ~ 1/226 MW$_c$h/$ (EIA 1998). A lower bound would be that associated with the least energy intensive manufactured product group, which in the U.S. in 1994 was apparel and other textile products, with $1/\eta_{\mu} \sim 0.47$ kBtu/\$ $\sim 1/7{,}260$ MW_ch/\$ (EIA 1998).

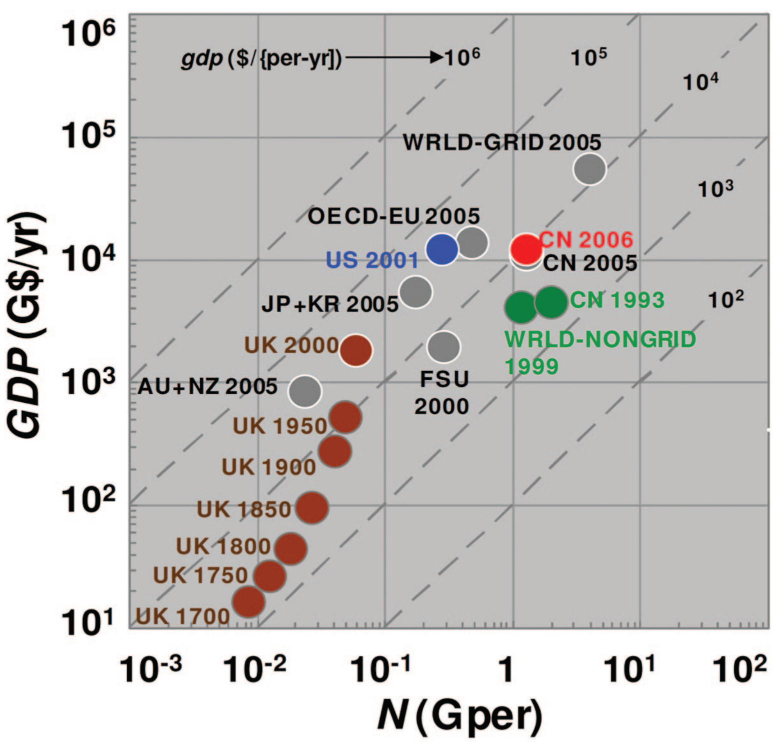
Using these estimates for the first two terms and the bounds for the third term, the ratio, $\dot{e}_{\Phi,\mathrm{cap}}/\dot{e}_{\Phi,\mathrm{op}}$, between the energy embodied in the capital cost of light to the energy associated with the operating cost of light can then be bounded between 1/24 and 1/778. These bounds are consistent with ratios of 1/90 and 1/400 found in a study (Gydesen and Maimann 1991) in which 15W compact fluorescent and 60W incandescent lamps, respectively, were dissected into their material contents and embodied energies, and the embodied energies compared to their lifetime energies of operation. They are also consistent with ratios of 1/215, 1/64 and 1/66 found more recently for similarly dissected incandescent, compact fluorescent and LED lamps (Siemens AG 2009).

We conclude that the energy embodied in the capital cost of light is negligible, and for the remainder of this paper we assume that Equation (2) holds for the relationship between consumption of light and consumption of associated energy, both for the U.S. in 1994 as well as for all other nations in all other years.

2.6 GROSS DOMESTIC PRODUCT AND POPULATION

As we shall see in Section 3, gross domestic product (*GDP*) and population (*N*) are key factors underlying consumption of light, so we have gathered together various estimates for these. These estimates are listed in Table 1, and plotted in Fig. 2.

Fig. 2. Scatterplot of gross domestic product (*GDP*) and population (*N*) associated with the five datasets discussed in Section 2. Country abbreviations are given in the caption to Table 1. The dashed diagonal lines are contours of constant per-capita gross domestic product (*gdp*).



For individual nations our primary sources for historical and contemporary gross domestic products and populations were the comprehensive databases compiled by Angus Maddison (Maddison 2007) and the University of Groningen

(GGDC 2007). Importantly, the *GDPs* in these databases were derived using purchase-power-parity, rather than exchange-rate, methods. Although we do not pursue this issue further in this paper, we mention here that we did find that consumption of light had a significantly stronger correlation with such purchase-power-parity *GDP*s than with exchange-rate *GDP*s.

For most of the groups of nations, we simply summed the *GDP*s or populations of the individual nations. In the few cases where *GDP* or *N* for a particular year was not in the database, simple geometric interpolation between years was done.

To estimate *GDPs* and populations of those with (WRLD-GRID 2005) and those without (WRLD-NONGRID) access to grid electricity, we approximate the first to be those nations classified by the World Bank (WB, 2007) as middle or high income, and the second to be those classified as low income. Doing so for the first in 2005 yields a population of 4.1 Gper and a *GDP* of 54.8 G$/year, numbers we associate with the estimates in the IEA dataset of world consumption of light from grid electricity in 2005. Doing so for the second in 1999 yields a population of 2.1 Gper and a *GDP* of 4.6 G$/year. We note that this population is very close to the estimate in the Mills dataset of 2.0 Gper without access to grid electricity in 1999. Since the deviation is small, and since we would like to use without modification Mills' associated estimates of the consumption of light, for our purpose we accept his estimate of 2.0 Gper and simply scale *GDP* proportionately down to (2.0/2.1) · 4.6 G$/year=4.4 G$/year.

3 RELATIONSHIP BETWEEN CONSUMPTION OF LIGHT, INCOME AND PRICE

In this Section, we describe what we have found to be the primary relationship governing consumption of light: that per-capita consumption of light varies linearly with the ratio between per capita gross domestic product and cost of light. We then discuss how this primary relationship can be improved slightly through higher-order nonlinear relationships with per capita gross domestic product and cost of light, though the introduction of such relationships is not yet believed warranted by the accuracy of the underlying data.

3.1 RELATIONSHIP BETWEEN φ AND *gdp/CoL*

The central result of this paper is that per-capita consumption of light is, to a good approximation, linearly proportional to the ratio between per capita gross domestic product and cost of light, obeying the expression:

$$\varphi = \beta \cdot \frac{gdp}{CoL}\,. \tag{5}$$

The surprising descriptive power of this expression is illustrated[8] in Fig. 3. The vertical axis of the Figure is per-capita consumption of light, φ, in units of Mlmh/(per-yr). The horizontal axis of the Figure is β, a dimensionless proportionality constant, times per-capita gross domestic product, *gdp*, in units of $/(per-yr), divided by cost of light, *CoL*, in units of $/Mlmh. Because the two axes have the same units, Mlmh/(per-yr), Fig. 3 basically plots direct estimates of per-capita consumption of light in a number of nations or groups of nations (vertical axis) against indirect predictions of per-capita consumption of light

[8] Note that, since the axes of Figure 3 are logarithmic, we have effectively plotted the logarithmic form of Equation (5): $\log(\varphi) = \log(\beta) + \log(gdp) - \log(CoL)$.

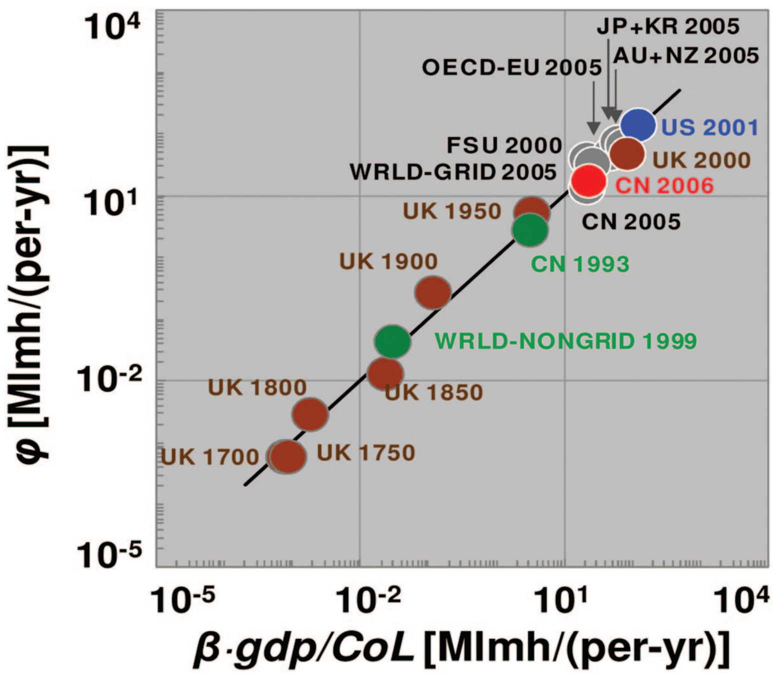


Fig. 3. Data for per-capita consumption of light (φ) plotted against the product of a constant factor (β) and per capita gross domestic product (*gdp*), divided by the cost of light (*CoL*). Country abbreviations are given in the caption to Table 1. The diagonal black line has slope unity and zero offset.

based on independent estimates of *gdp* and *CoL* in those same nations or groups of nations (horizontal axis).

As illustrated in Fig. 3, per-capita consumption of light is predicted remarkably well by 5, despite a span of data over: 3 centuries (1700–2006), 6 continents (Africa, Asia, Australia, Europe, North America, South America), 5 types of fuel (tallow, whale oil, gas, petroleum, electricity), 5 overall families of lighting technologies (candles, oil lamps, gas lamps, electric incandescent bulbs, electric gas-discharge bulbs or tubes), 1.4 orders of magnitude in per capita gross domestic product, 4.3 orders of magnitude in cost of light, and 5.4 orders of magnitude in per-capita consumption of light.

That per-capita consumption of light varies so simply with the ratio between *gdp* and *CoL* seems fortuitous,[9] but allows for the following "physical" interpretation. People expend a fixed fraction (β) of their *gdp* on light, and per-capita consumption of light is simply this expenditure (β·*gdp*) divided by the cost of light (*CoL*). The fixed fraction can be determined, by a least squares fit of log(φ) to log(β·*gdp*/*CoL*), to be $\beta = 0.0072$.[10] More precisely, logarithmic regression gives log(β)= -2.15 ± 0.26 FWHM, with an adjusted coefficient of determination R^2=

[9] Indeed, this variation is so simple that it suggests a tautology: a mutual dependence of φ, *gdp* (as deduced from *GDP* and *N*), and *CoL* (as deduced from η_φ and *CoE*) on some underlying single variable. We cannot rule this out, but do not see any obvious candidates.

[10] This procedure gives a β which is essentially the mean of the values for φ·*CoL*/*gdp* for all of the data points (see Table 1), weighted equally. We could instead have taken β to be the value of φ·*CoL*/*gdp* associated with the data point considered most accurate: the comprehensive Navigant study of the 2001 U.S. lighting market (Navigant 2002), which self-consistently aggregated bottom-up surveys, audits and inventories from a large number of independent sources. Doing so would give a β which is slightly lower, 0.0067 rather than 0.0072.

0.986.[11] Note that on an absolute scale the confidence interval for β is not small: its lower end is $\beta= 10^{-2.15-0.26}$=0.0039 and its upper end is $\beta=10^{-2.15+0.26}$ =0.0130. This range of $10^{2 \cdot 0.26}$=3.3 is infinitesimal, however, compared to the dynamic range of $10^{5.36}$=230,000 for per-capita consumption of light itself.

Indeed, it is the wide dynamic range of the data that enables us to have confidence in the observed empirical trend in per-capita consumption of light. As discussed in Section 2, the various estimates of per-capita consumption of light, per-capita gross domestic product and cost of light are fraught with difficulty. Nevertheless, even errors at the high end of likelihood (factors of 2–3x for any individual data point) are small compared to the dynamic range of 230,000 of the entire data set.

We conclude that, to a very good approximation, people in nations over diverse temporal, geographic, technological and economic circumstances[12] have expended 0.39 percent to 1.30 percent (with a best fit value of 0.72 percent) of their *gdp* on light.[13] We also conclude that the income elasticity (at constant price) and the price elasticity (at constant income) of the demand for light are both unity or nearly unity.

At first blush, such high elasticities are surprising, given the widely made assumption that demand for light is independent of efficiency (and hence cost), and the also widely made corollary assumption that energy consumption will decrease as technology evolution leads to improvement in lighting efficiency (BES 2006; Kendall and Scholand 2001; Navigant 2006; Tsao 2002).

At second blush, however, such high elasticities for lighting, over decades-to-centuries time periods, are perhaps not so surprising. The human visual system is among the most complex and developed of our sensory systems, and is key to how we experience the world around us. Humans are not indifferent to ways of enhancing this experience, including through use of artificial light. One can only speculate how altered the architecture of enclosed spaces and buildings would need to be if only natural sun- and moon-light were available to be exploited, and how expensive it would be to substitute enough capital, labor and materials to compensate.

Moreover, though an expenditure of 0.72 percent of *gdp* on any single good or service seems like a significant fraction, on an absolute scale it is relatively small. Hence, one can anticipate that it would be relatively painless in economic terms to maintain its magnitude under diverse temporal, geographic, technological, and economic circumstances, particularly if the consumption of light confers significant benefit to the productivity and quality of human life.

Finally, we point out that the empirical relationship between φ, *gdp* and *CoL* is not intended to be interpreted as a dependency of φ on *gdp* and *CoL* as independent variables. More likely, the three are self-consistently interdependent: if *CoL* were to decrease, φ might increase; as φ increases, human

[11] The adjusted and non-adjusted coefficients of determination are virtually the same, due to the large number (seventeen) of samples compared to the number (one) of fitting parameters.

[12] We especially call attention to the WRLD-NONGRID 1999 data point, which corresponds to the fuel-based lighting consumed by those in the modern world without access to grid electricity. This data point falls very closely on the straight line drawn in Figure 3, indicating that the poor (whether in modern or historical times) do *not* spend a disproportionately larger (or smaller) fraction of income on light than do the wealthy.

[13] Note that while the confidence interval encompasses the percentage, 1.2%, found in the recent International Energy Agency study (IEA, 2006), the best-fit value, 0.72%, is somewhat lower. The reasons are twofold: the IEA's use of exchange-rate based, but our use of purchase-power-parity based, *gdps*; and the IEA's estimates of $\varphi \cdot CoL/gdp$ being slightly high relative to those of the other datasets.

productivity associated with the consumption of light might increase; as human productivity increases, *gdp* might increase; and as *gdp* increases, investment in technology development might lead to further decreases in *CoL*.

3.2 OTHER POSSIBLE RELATIONSHIPS BETWEEN φ, *gdp* AND *CoL*

Though the simple linear variation of per-capita consumption of light on the ratio between *gdp* and *CoL* is striking, it is interesting to explore other possible variations.

3.2.1 φ VARIES SOLELY WITH EITHER *gdp* OR *CoL*

The simplest of these would be a variation of φ solely with either *gdp* or *CoL*. After all, over historical time, *gdp* has generally increased while *CoL* has generally decreased, and one might anticipate that consumption of light could be predicted using either variable alone.

To see how, we show the two variations in Fig. 4a and 4b. If we assume simple power-law variations, then logarithmic regressions give two two-parameter fits: $\log(\varphi)=-13.64+\log(gdp^{3.52})$ and $\log(\varphi)=2.01+\log(CoL^{-1.15})$. Because the 5.4 orders-of-magnitude variation in φ is larger than either the 1.3 orders-of-magnitude variation in *gdp* or the 4.3 orders-of-magnitude variation in *CoL*, the absolute magnitudes of the power-law exponents must both be larger than unity: 3.52 for the variation with *gdp* and -1.15 for the variation with *CoL*. The adjusted coefficients of determination are $R^2= 0.766$ for the variation with *gdp*, and $R^2= 0.958$ for the variation with *CoL*. Though these adjusted coefficients of determination for the two *two*-parameter fits are in a reasonable range, neither is as high as the $R^2= 0.986$ found for the *one*-parameter fit to a linear variation with *gdp*/*CoL*.

Moreover, closer inspection of Fig. 4a and 4b indicates plausible explanations for the lower adjusted coefficients of determination. Consider Fig. 4a, which plots φ against *gdp*. Per-capita consumption of light has a larger apparent variation with *gdp* for the *CoL*>\$10/Mlmh (mostly fuel-based) data points than for the *CoL*<\$10/Mlmh (mostly grid-electricity) data points. A plausible explanation is that, for the former but not for the latter, the variation in *gdp* is augmented by a large but hidden variation in *CoL*.[14] Likewise, consider Fig. 4b, which plots φ against *CoL*. Here, the situation is reversed. Consumption of light has a larger apparent variation with *CoL* for the *CoL*<\$10/Mlmh (mostly grid-electricity) data points than for the *CoL*>\$10/Mlmh (mostly fuel-based) data points. A plausible explanation is that, for the former, *CoL* varies hardly at all, hence most of its variation in consumption of light is due to the large (but hidden) variation in *gdp*.

Of course, it is still *possible* that consumption of light varies either solely with *gdp* or with *CoL*, but that the variations are piecewise, with different power-law exponents for *CoL*<\$10/Mlmh than for *CoL*>\$10/Mlmh. For example, all that would be necessary for consistency with Fig. 4a would be for the magnitude of the power-law exponent with respect to *gdp* to be relatively large (~4.7) for *CoL*>\$10/Mlmh, then to become relatively small (~1.5) for *CoL*<\$10/Mlmh. Likewise, all that would be necessary for consistency with Fig. 4b would be for

[14] Note that if only the grid electricity datapoints are used, *gdp* is at least an *approximate* predictor for consumption of light. But *CoL* still plays a role, as can be seen from a compilation of data from 33 countries by Mills (Mills 2002) in which Norway is an outlier, most likely because of its low hydroelectricity cost and hence low *CoL*.

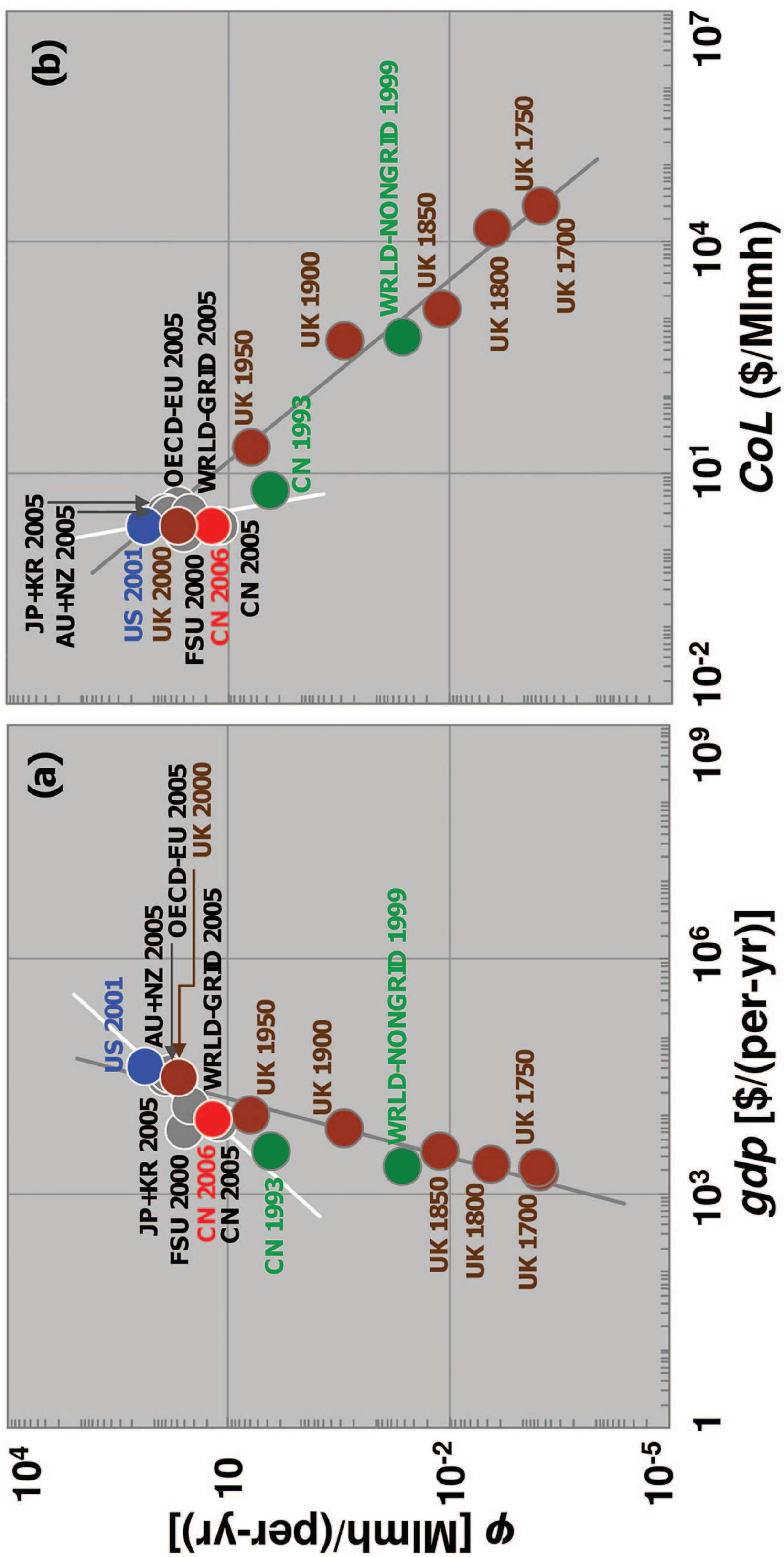


Fig. 4. Data for per-capita consumption of light (φ) vs. (a) per capita gross domestic product (*gdp*) and (b) cost of light (*CoL*). Country abbreviations are given in the caption to Table 1. The black and white diagonal lines are independent power-law fits to the *CoL*>$10/Mlmh (outlined in white) and *CoL*<$10/Mlmh (outlined in dark gray) data points, respectively, and are intended to visually illustrate the different dependences on *gdp* and *CoL* of these data points.

the magnitude of the power-law exponent with respect to *CoL* to be relatively small (~-1.3) for *CoL*>\$10/Mlmh, then to become relatively large (~-6) for *CoL*<\$10/Mlmh.

Although neither larger-than-unity nor piecewise changes in power-law exponents can be ruled out, we do not find any reason to invoke them. Instead, Occam's Razor suggests that it is more likely that per-capita consumption of light varies similarly with the ratio between *gdp and CoL* for all *CoL* values, energy sources and data sets.

3.2.2 NONUNIT ELASTICITIES

Another possible variation is one in which the variations of φ on *gdp* and *CoL* are power law but not with unit elasticities. The dependence that is most consistent with the data is one in which consumption of light varies with *gdp* and *CoL* as

$$\varphi = \frac{0.0025 \cdot gdp^{1.08}}{CoL^{0.90}}, \tag{6}$$

with a (logarithmic) adjusted regression coefficient of determination that is increased (very slightly) to R^2=0.989. The implication would be that the income elasticity (at constant price) of light consumption is slightly (8 percent) greater than unity, while the price elasticity (at constant income) of light consumption is slightly (10 percent) less than unity.

We note, however, that these deviations from nonunity elasticities of demand are small and, in our judgment, give insignificant improvement in consistency with the data compared to the likely errors in the data points themselves. As was discussed in in Section 2, each data point is associated with independent estimates of *three* quantities (φ, *gdp*, *CoL*). These estimates, made over diverse temporal, geographic, technological, and economic circumstances, are fraught with potential for error, particularly for the data points going back furthest in time, when the mixes of fuel and lamp technologies were undergoing radical changes.

3.2.3 VARIATION OF β WITH *gdp*

A third possible variation might be one in which the proportionality factor β itself depends on per-capita gross domestic product. If we assume an exponential form to that dependence, then we find that β= 0.0056 + 0.0109·exp(-*gdp*/*gdpo*), where *gdpo*=6,300 \$/(per-yr). The fit to the data improves, but because there are more fitting parameters, the adjusted (logarithmic) regression coefficient of determination does not improve, but stays the same at R^2= 0.986. We find no reason to invoke this more complex variation, but cannot rule out the notion that β, the fraction of *gdp* spent on lighting, decreases slightly with *gdp*.[15]

4 IMPLICATIONS ON WORLD CONSUMPTION OF LIGHT AND ASSOCIATED ENERGY

In Section 3 we discussed how per-capita consumption of light depends on the ratio between per-capita gross domestic product and cost of light. In this

[15] We acknowledge Peter Dempster for prompting us to examine dependences of β on *gdp*.

Section, we discuss the implications of this dependence on world consumption of associated energy.

4.1 RELATION BETWEEN CONSUMPTION OF LIGHT AND ASSOCIATED ENERGY

To start, note that, as discussed in Section 2, luminous efficacy connects two pairs of quantities. The first pair is per-capita consumption of light and per-capita consumption of associated energy, through Equation (2): $\dot{e}_\Phi = \varphi/\eta_\varphi$. The second pair is cost of light (*CoL*, in units of \$/Mlmh) and cost of associated energy (*CoE*, in units of \$/MW$_e$h), through Equation (4): $CoL = (1+\kappa_\varphi)\cdot CoE/\eta_\varphi$. Thus, we can rewrite Equation (5) as

$$\dot{e}_\varphi = \beta \cdot \frac{gdp}{(1+\kappa_\varphi)\cdot CoE}. \tag{7}$$

Likewise, we can replot the data of Fig. 3 using the modified axes in Fig. 5. Because Equation (7) is essentially equivalent to Equation (5), the data points in Fig. 5 fall on a (logarithmic) unit-slope line just as did those in Fig. 3. However, because luminous efficacy varies between time periods and between nations, the relative placements of the data points are not the same.

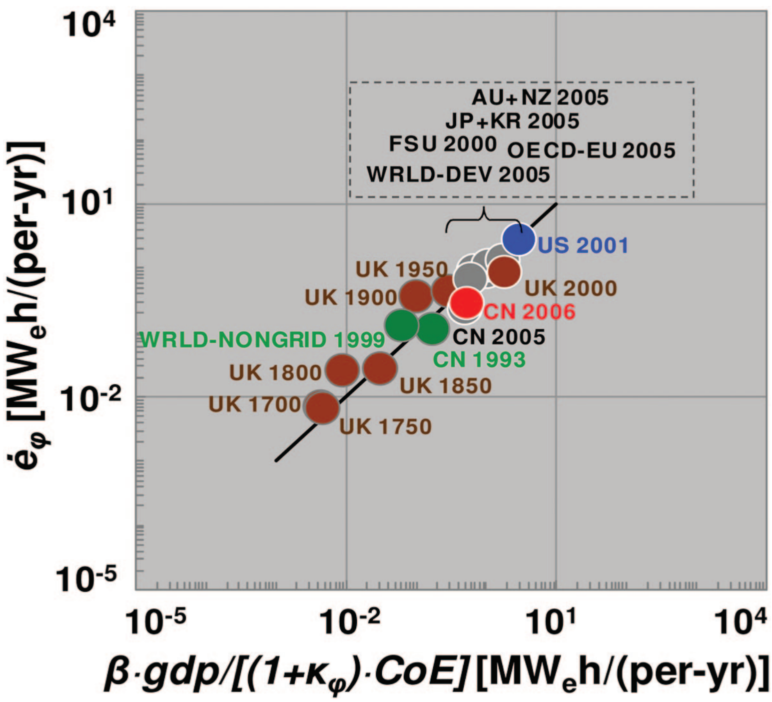


Fig. 5. Data for per-capita consumption of energy associated with consumption of light, plotted against the product of a constant factor (β) and per capita gross domestic product (*gdp*), divided by a factor that accounts for the operating and capital cost of light ($1+\kappa_\varphi$) and by cost of energy (*CoE*). Country abbreviations are given in the caption to Table 1. The diagonal black line has slope unity and zero offset.

Also note that per-capita consumption of associated energy does not span as wide a dynamic range (2.6 orders of magnitude) as per-capita consumption of light (5.4 orders of magnitude). The reason is that, as discussed in Section 2, cost of energy does not span as wide a range as cost of light, due to the steady advancement, over the centuries, in luminous efficacy.

4.2 WORLD CONSUMPTION OF LIGHT AND ASSOCIATED ENERGY

Up until now, we have dealt exclusively with per capita quantities for consumption of light and associated energy. It is also of interest to estimate *total* human consumption of light and associated energy, by multiplying by world population, *N*:

$$\Phi = N \cdot \varphi = \beta \cdot \frac{GDP}{CoL} \tag{8a}$$

$$\dot{E}_\Phi = N \cdot \dot{e}_\varphi = \beta \cdot \frac{GDP}{(1 + \kappa_\varphi) \cdot CoE} \,. \tag{8b}$$

In particular, we can estimate, using Equations (8a) and (8b), world consumption of light and associated energy in 2005. As for all other estimates, we use estimates of *GDP* based on Maddison's work (GGDC 2007), EIA estimates for average price of energy, and light-consumption-weighted inverse luminous efficacies, all listed in Table 1. The result is an estimated world 2005 consumption of light and associated energy of 130 Plmh/year and 2.7 PW_eh/year, respectively. This represents about 16 percent of the world's total electrical energy generation of about 16.9 PW_eh/year in 2005 (EIA 2007c). And, since 2.7 PW_eh/year of electrical energy is equivalent to roughly 8.5 PW_ch/year and 29.5 Quads/year of primary chemical energy, this represents about 6.5 percent of the world's consumption of 457 Quads/year of primary energy in 2005 (EIA 2007c).

Note that lighting therefore represents a much larger (6.5 percent) percentage of world energy consumption than of *GDP* (0.72 percent). This is an indication of the very high energy intensity of lighting relative to other goods and services, and hence the reasonableness of its classification, along with heat, power and transportation, as an "energy service."

5 SUMMARY AND FUTURE DIRECTIONS

We have self-consistently analyzed data for per-capita consumption of artificial light, per-capita gross domestic product, and cost of light. The data span a wide range: 3 centuries (1700–2006), 6 continents (Africa, Asia, Australia, Europe, North America, South America), 5 types of fuel (tallow, whale oil, gas, petroleum, electricity), 5 overall families of lighting technologies (candles, oil lamps, gas lamps, electric incandescent bulbs, electric gas-discharge bulbs or tubes), 1.4 orders of magnitude in per-capita gross domestic product, 4.3 orders of magnitude in cost of light, and 5.4 orders of magnitude in per-capita consumption of light.

We find that the data are consistent with a simple expression in which per-capita consumption of artificial light varies linearly with the ratio between per-capita gross domestic product and cost of light. The expression is plausible, but we make no serious attempt to explain its origin. Instead, we consider its explanation (both for developing and developed countries) an interesting direction for future work, and at present consider it to be simply an empirical result, though one with important implications.

A first implication is that, extrapolated and aggregated to the world in 2005, 0.72 percent of world gross domestic product and 6.5 percent of world primary energy was expended to purchase 130 Plmh of artificial light at a primary energy cost of 29.5 Quads.

A second implication is that it represents the historically consistent baseline assumption for constructing future scenarios for consumption of light and associated energy. In other words, there is a massive *potential* for growth in the consumption of light if new lighting technologies are developed with higher luminous efficacies and lower cost of light. Indeed, this empirical result has powerful implications on the rebound effect discussed in the Introduction, and an important direction for future work will be to understand quantitatively these implications.

Finally, we believe another possible direction for future work would be to extend this empirical work on the consumption of artificial light to the consumption of other energy services (for example, transportation). It would be especially interesting to combine, as has been done here, historical time-series with contemporary cross-sectional data. In this way, one could gain a broader understanding of the rebound effect not just on the relatively short (months to years) time periods during which societal-use paradigms for an energy service are relatively static, but over the longer (decades to centuries) time periods during which radically new societal-use paradigms emerge, with associated radical changes in consumption of that service.

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REFERENCES

Alcott B. 2005. Jevons' paradox. Ecological Economics. 54(1):9–21.

Azevedo IL, Morgan MG, Morgan F. 2009. The Transition to Solid-State Lighting. Proceedings of the IEEE. 97(3):481–510.

BES. 2006. Basic Research Needs for Solid-State Lighting: U.S. Department of Energy, Office of Basic Energy Sciences.

Bowers B. 1998. Lengthening the day: a history of lighting technology. Oxford: Oxford University Press. 221 p.

Boyce PB. 2003. Human Factors in Lighting, 2nd Ed.: Taylor & Francis. 584 p.

Brookes L. 1990. The greenhouse-effect - the fallacies in the energy efficiency solution. Energy Policy. 18(2):199–201.

Denton T. 2004. Automobile Electrical and Electronic Systems: Elsevier. 463 p.

[DOE]. 2007. 2007 Buildings Energy Data Book. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

Dowling K. 2003. The Cost of Light, Color Kinetics Whitepaper. http://www.colorkinetics.com/whitepapers/CostofLight.pdf.

[DOE] US Department of Energy. 2009. Solid-State Lighting Multi-Year Program Plan FY'09-FY'15: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

[EIA] Energy Iinformation Admidistration. 1998. Changes in Energy Intensity in the Manufacturing Sector 1985–1994.

[EIA] Energy Iinformation Admidistration.2007a. Annual Energy Outlook 2007 with Projections to 2030 (http://www.eia.doe.gov/oiaf/aeo/pdf/0383.

[EIA] Energy Iinformation Admidistration. 2007b. Electricity Prices for Selected Countries, Recent Years (http://www.eia.doe.gov/emeu/international/electricityprice.html)

[EIA] Energy Iinformation Admidistration. 2007c. International Energy Outlook 2007 (http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2007).

Fouquet R, Pearson PJG. 2006. Seven Centuries of Energy Services: the Price and Use of Light in the United Kingdom (1300–2000). Energy Journal, 27(1):139–177.

[GGDC] Groningen Growth and Development Centre. 2007. Total Economy Database. (http://www.ggdc.net/)

[GIA] Global Industry Analysts . 2008. Lighting Fixtures: A Global Strategic Business Report. (http://www.ledsmagazine.com/news/4/8/3).

Greening LA, Greene DL, Difiglio C. 2000. Energy Efficiency and Consumption - the Rebound Effect - a Survey. Energy Policy. 28(6–7):389–401.

GTZ. 2007. International Fuel Prices. Federal Ministry for Economic Cooperation and Development (Germany).

Gydesen A, Maimann D. 1991. Life cycle analyses of integral compact fluorescent lamps versus incandescent lamps. Proceedings of Right Light 1: Policy and Planning Issues (Stockholm, Sweden).

[IEA] International Energy Agency. 2006. Light's Labour's Lost: Policies for Energy-efficient Lighting: International Energy Agency.

Jevons WS. 1906. The Coal Question: An Inquiry concerning the progress of the nation and the probable exhaustion of our coal-mines: Macmillan and Co.

Kanellos M. 2008. The Global Lighting Market by the Numbers, Courtesy of Philips. Seeking Alpha (http://seekingalpha.com/article/101408-the-global-lighting-market-by-the-numbers-courtesy-of-philips).

Kendall M, Scholand M. 2001. Energy Savings Potential of Solid State Lighting in General Lighting Applications. [0.5]. U.S. Department of Energy, Office of Building Technology, State and Community Programs.

Khazzoom JD. 1980. Economic implications of mandated efficiency in standards for household appliances. Energy Journal, 1(4):21–40.

Krames MR, Shchekin OB, Mueller-Mach R, Mueller GO, Zhou L, Harbers G, et al. 2007. Status and future of high-power light-emitting diodes for solid-state lighting. Journal of Display Technology. 3(2):160–175.

Li JM. 2007a. Estimate of consumption of light and associated energy in China 2006. Unpublished.

Li JM. 2007b. Estimates of the cost of electricity in China 1993–2006. Unpublished.

Maddison A. 2007. World Population, GDP and Per Capita GDP, 1–2003 AD.

Mills E. 2005. Environment - the Specter of Fuel-Based Lighting. Science. 308(5726):1263–1264.

Min GF, Mills E, Zhang Q. 1997. Energy Efficient Lighting in China - Problems and Prospects. Energy Policy. 25(1):77–83.

MW. 2009. Measuring Worth: A Service for Calculating Relative Worth over Time. http://www.measuringworth.com/index.html.

Navigant. 2002. U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

Navigant. 2003. Energy Savings Potential of Light Emitting Diodes in Niche Lighting Applications. Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

Navigant. 2006. Energy Savings Potential of Solid State Lighting in General Illumination Applications. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

Nordhaus WD. 1997. Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not. In T. F. Breshnahan and R. J. Gordon (Eds.), The Economics of New Goods (pp. 29–70). Chicago: The University of Chicago Press.

Rea MS, editor. 2000. The IESNA Lighting Handbook. New York: Illuminating Engineering Society of North America.

Rosenberg N. 1982. Inside the Black Box: Technology and Economics: Cambridge University Press.

Saunders HD. 1992. The Khazzoom-Brookes postulate and neoclassical growth. The Energy Journal. 13(4):131–148.

Schivelbusch W. 1988. Disenchanted Night: The Industrialization of Light in the Nineteenth Century: The University of California Press. 227 p.

Schubert E, Kim J, Luo H, Xi J. 2006. Solid-state lighting-a benevolent technology. Reports on Progress in Physics. 69(12):3069–3099.

Shur MS, Zukauskas A. 2005. Solid-state lighting: toward superior illumination. Proceedings of the IEEE. 93(10):1691–1703.

Siemens AG, CT. 2009. Life Cycle Assessment of Illuminants: A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps (Executive Summary).

Tsao JY. 2002. Light Emitting Diodes (LEDs) for General Illumination Update 2002: Optoelectronics Industry Development Association.

Tsao JY. 2004. Solid-state lighting: lamps, chips and materials for tomorrow. IEEE Circuits and Devices Magazine. 20(3):28–37.

Tsao JY, Coltrin ME, Crawford MH, Simmons JA. 2009. Solid-State Lighting: An Integrated Human Factors, Technology and Economic Perspective. Proceedings of the IEEE (in press).

[UKERC] UK Energy Research Centre. 2007. The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency.

[WB] World Bank. 2007. World Bank List of Economies: World Bank.

XE. 2009. XE Interactive Currency Table. http://www.xe.com/ict/.